

## U.S. AGRICULTURE AND CLIMATE CHANGE: NEW RESULTS

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**Abstract.** We examined the impacts on U.S. agriculture of transient climate change as simulated by 2 global general circulation models focusing on the decades of the 2030s and 2090s. We examined historical shifts in the location of crops and trends in the variability of U.S. average crop yields, finding that non-climatic forces have likely dominated the north and westward movement of crops and the trends in yield variability. For the simulated future climates we considered impacts on crops, grazing and pasture, livestock, pesticide use, irrigation water supply and demand, and the sensitivity to international trade assumptions, finding that the aggregate of these effects were positive for the U.S. consumer but negative, due to declining crop prices, for producers. We examined the effects of potential changes in El Niño/Southern Oscillation (ENSO) and impacts on yield variability of changes in mean climate conditions. Increased losses occurred with ENSO intensity and frequency increases that could not be completely offset even if the events could be perfectly forecasted. Effects on yield variability of changes in mean temperatures were mixed. We also considered case study interactions of climate, agriculture, and the environment focusing on climate effects on nutrient loading to the Chesapeake Bay and groundwater depletion of the Edward's Aquifer that provides water for municipalities and agriculture to the San Antonio, Texas area. While only case studies, these results suggest environmental targets such as pumping limits and changes in farm practices to limit nutrient run-off would need to be tightened if current environmental goals were to be achieved under the climate scenarios we examined



## 1. Introduction

There have been many studies of the potential impacts of climate change on U.S. agriculture but all have limitations as discussed in recent reviews and as acknowledged in the studies themselves (Reily and Schimmelpfennig, 1999; Adams et al., 1998; Mendleson, 2001; Easterling et al., 1993; Adams and McCarl, 2001; Adams et al., 2001). Past studies have used doubled-CO<sub>2</sub> equilibrium climate scenarios usually without aerosols rather than more realistic transient climate scenarios driven by gradually increased greenhouse gas forcing. Past studies also have not considered the climate change impacts on agricultural pesticide use, or on the environment via climate-induced changes in agricultural resource use. The impacts of changes in climate variability have also been overlooked. The potential for the agricultural economy to adapt to climate change has received much attention but research remains inconclusive because of the difficulty of providing complete tests of competing hypotheses (Reilly and Schimmelpfennig, 2000; Schneider et al., 2000).

While a variety of caveats and open issues remain this study represents the most comprehensive study to date on agricultural impacts of climate change in the U.S. This comprehensiveness was accomplished by building carefully on the models and methods that have been developed over the past. The study had three broadly separate components: (1) an analysis of historical variability in crop yields and movement of cropping across the United States, (2) an integrated set of simulation studies of the impacts of future climate change on the agriculture sector, (3) modeling case studies of variability and of regions with vulnerable resources. Our discussion is also backed by a more complete report (Reilly et al., 2002).

## 2. Historical Changes in U.S. Agriculture and Climate

We asked 2 questions about the past 100 years that have a bearing on climate and agriculture interactions. These were: (1) Has aggregate U.S. yield variability changed over the past century? and (2) How has the production of major crops relocated geographically? We did not seek to quantitatively evaluate the causes for the observed trends, but rather attempted simply to establish factual evidence regarding these questions as a background against which to think about the effects of future climate change. We discuss some of the factors that might be responsible and whether the changes are consistent with observed patterns of historical climate change, but establishing quantitative evidence for the role of climate or other factors, would require further investigation.

To consider trends in yield variability, we used USDA data on the average U.S. yield for 3 crops (maize, wheat, and potatoes) for the period 1866 to 1998.

Yield variation ( $V$ ) was measured as the relative deviation from the 9-year moving average. Specifically:

$$V = \text{absolute value of } (X_t - X_{\text{trend}}) / X_{\text{trend}}, \quad (1)$$

where  $X_t$  is crop yield in year  $t$  in tons per hectare and  $X_{\text{trend}}$  is the 9-year moving average of yield in tons per hectare. Year  $t$  was the 5th year of each 9-year average, i.e., the center point. The actual data available for evaluating the trend in variability thus ran from 1870 to 1994, as we lost 4 years at the beginning and end of the series because of the need to compute the 9-year moving average. The trend in yield variation we used was an estimate of coefficient  $\beta$  from the linear regression model

$$V = \alpha + \beta t. \quad (2)$$

A negative value of  $\beta$  thus reflects a decline in variation whereas a positive value indicates an increase in variation, and its magnitude is an estimate of a percentage change in the deviation from the 9-year average. For example, the point estimate result (Table I) for maize for the period 1870 to 1994 was a decline in variability of yield by 0.0127% but the standard error of the estimate was 0.0162 and so this change is not significantly different than zero at either the 5 or 10% significance levels. Variation for wheat and potatoes declined and this estimate was statistically significant over the entire period and for the sub-period 1900–1994. The significance disappears for the shorter period of 1950–1994 for these two crops. While trends for the longer period are statistically significant the point estimate of the change in the variation is virtually zero, i.e.,  $\ll 1\%$  per year. The maize results are essentially the opposite those for wheat and potatoes, statistically insignificant for the longer periods, but significant and showing an increase in variation between 1950 and 1994. The magnitude of the trend is larger but still  $< 1\%$  year.

We note several aspects of this analysis as important to consider in interpreting the results. One is that the measure of variation is as percent of yield, closely related to a more standard measure of variability such as the coefficient of variation. In the latter part of this period, particularly since 1950, yields increased dramatically. Maize yield increased by nearly  $3\frac{1}{2}$  times, potatoes by nearly 3 times, and wheat yields by  $2\frac{1}{4}$  times from 1950 to 1994 (Reilly and Fuglie, 1998). Hence, with relative variation little changed, the absolute variation in tons per hectare obviously increased by the same amounts that average yields increased.

A second aspect of this analysis is that we intentionally chose crops for which we had a very long time series, to try to investigate any impacts of long-term climate change as opposed to decadal changes. Variation in crop yields is quite high and so any hope to obtain statistically significant results required a long series of data. There are well-known periods like the dust-bowl of the 1930s that increase variability, and decades of relatively mild climates such as the 1960s that decrease variability. Thus, one might see an apparent trend of increasing or decreasing vari-

Table I  
Trends in yield variation for 3 crops, (change in variation measured as a percent of the mean variation)

Commodity	Area harvested in 1997 (000 ha)	Area irrigated in 1997 (%)	Variation in crop yield from trend (estimates are in percent with the standard error of the estimates in parentheses)					
			1870–1994		1900–1994		1950–1994	
			Mean variation	Trend in variation	Mean variation	Trend in variation	Mean variation	Trend in variation
Maize	28,258	15.2	7.77 (0.58)	-1.271E-2 (1.620E-2)	7.24 (0.68)	1.553E-2 (2.480E-2)	6.97 (0.89)	2.357E-1 <sup>b</sup> (5.938E-3)
Wheat	23,820	6.8	6.28 (0.45)	-2.834E-2 <sup>b</sup> (1.230E-2)	5.86 (0.51)	-3.122E-2 <sup>a</sup> (1.81E-2)	4.92 (0.63)	-5.662E-4 (4.719E-2)
Potato	549	79.0	5.75 (0.52)	-8.159E-2 <sup>b</sup> (1.237E-2)	4.40 (0.46)	-7.608E-2 <sup>b</sup> (1.457E-2)	2.42 (0.30)	-4.076E-3 (2.211E-2)

<sup>a</sup> Significant at 10% level.

<sup>b</sup> Significant at 5% level.

ability that depended on the particular starting point, particularly for a short series of only a few decades.

A third aspect of this analysis is that we used average yield data for the United States as a whole rather than data at specific sites. Our focus was on the national scale and thus aggregate data automatically weights all the local changes. One consequence is that yield variation is generally less than one would observe at any particular site or at smaller aggregations because there is not perfect correlation among sites. A further consequence of using aggregated data is actual yield variability at many, or even at all sites could, for example, increase but aggregate variability might still decrease.\*

A fourth aspect of the analysis is that we used actual yields obtained by commercial farms (as opposed to controlled experimental data). A consequence of this plus the use of aggregate data is that the observed yield includes adaptive responses to any underlying physical and biological processes that contribute to changes in variability of yield (e.g., weather). Adaptations at specific sites might be expected to include irrigation, changing cultivars, or shifting out of that crop to another. Changes in the crop grown at specific sites might then be reflected in the aggregate data as less variability if production for a crop was concentrated toward those areas that were less subject to natural variability. Thus, the aggregate data would reflect all adaptive responses but might mask trends at individual sites. The final estimate is thus the resultant change in crop yield variability at the national level, including all processes human, technological, or natural that might have contributed to either an increase or decrease in variability. For our national focus, this aggregate result is a useful perspective.\*\*

We also constructed the geographic centroid of production for maize, soybean and wheat and plotted its movement from 1870 (1930 for soybean) to 1990. Data were for states and the assigned state location was the state's center. States were weighted by the actual total state production of the crop. There were substantial geographic shifts in production over the past 100 years of the three major crops we considered (Figure 1). The centroid of maize production moved more than 150 miles in a mainly westward direction between 1870 and 1900, then moved about 120 miles in a northward direction until 1980, and then moved mostly westward between 1980 and 1990. Wheat production shifted more than 500 miles steadily and primarily westward between 1870 and 1980. It shifted back slightly

\* Consider, for example, if there were two areas of production one with low variability (area A) and the other with high variability (area B). Suppose variability increases at both but even with this increase area A remains less variable than was area B at the beginning of analysis period. Further suppose, that virtually all production shifts to the area of low variability. In this case, aggregate variability of yield will decrease even though variability in both areas increased.

\*\* Of course there are many reasons to look at specific site data and to consider explicitly how changing practices at sites and changing location of production in response to changing variability (or for unrelated reasons) might affect variability in yield at various aggregations. However, it is important to recognize that very different results (even of direction) might be expected at different aggregations (i.e., as in previous footnote).

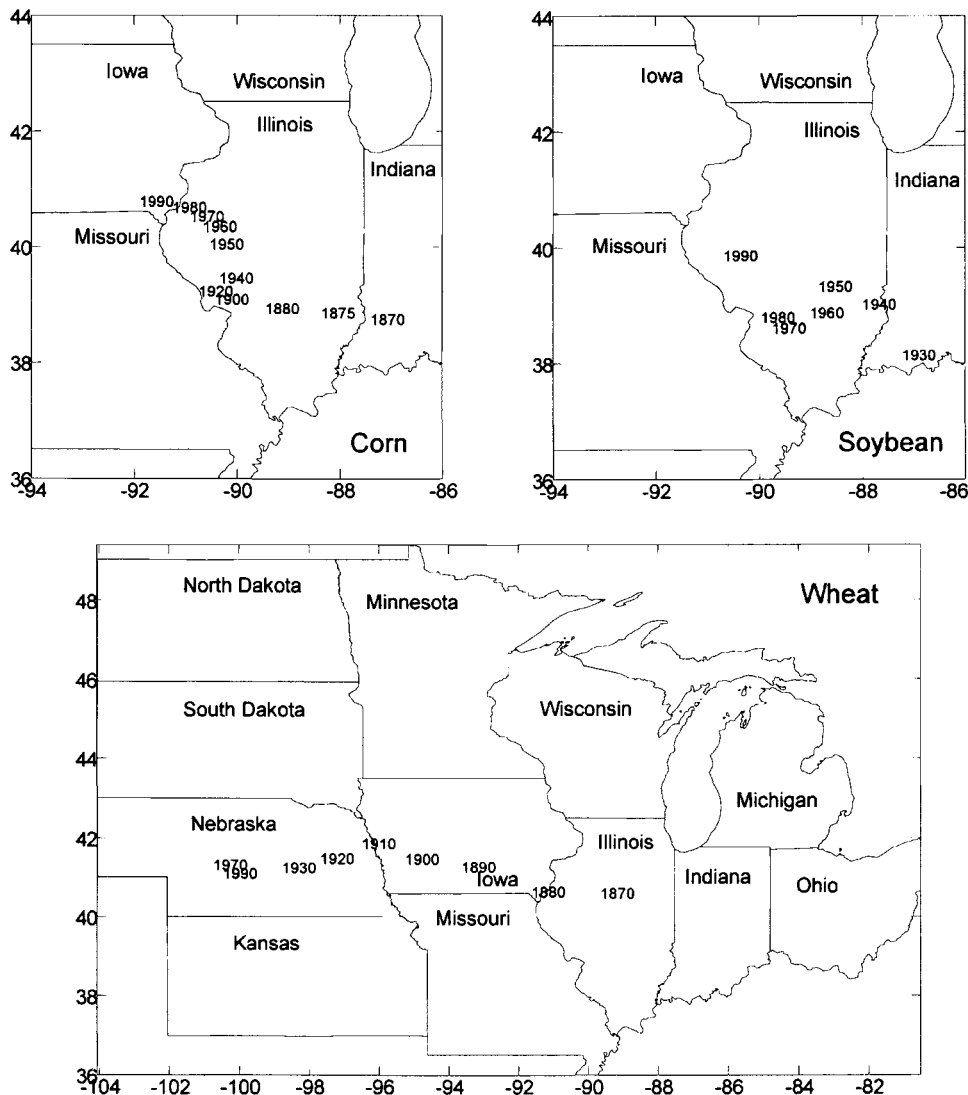


Figure 1. Shifts in the geographic center of production for 3 crops. The geographic center was calculated as the mean location using state level data for the entire U.S. weighting states by their production (maps show only that portion of the U.S. that contains the geographic center of production).

eastward between 1980 and 1990, remarkable only because it was the only reverse over the period. Soybean production shifted northward by more than 100 miles and westward by more than 200 miles between 1930 and 1990. Almost all of the northward shift occurred in first and last decades of this period.

As our focus was climate change and there is evidence that climate has changed over the past 100 years (Karl and Knight, 1998; Parker et al., 1994; Karl et al.,

1995; Easterling, 2002; Karl et al., 1996), an immediate question upon seeing these results was: Was climate change responsible for any of these shifts? Mostly, it appears that any affect the observed climate change has had on these national aggregate measures of crop yield variation and location was either negligible or overwhelmed by other changes. Computing the production-weighted mean temperature at which maize and soybeans were grown using the same data and methods as for identifying the centroid of production, we found that the mean temperature decreased by 4 °C over the period 1870 to 1990. This occurred despite an estimated warming trend for the U.S. as a whole of 0.6 °C (Karl et al., 1996). The northward shift of production was mainly responsible for this reduction in temperature, more than counteracting the warming that occurred at any site, and this Northward shift resulted in a 'climate change' for maize and soybean production of the order (though opposite in direction) of the predicted change over the next 100 years. The northward movement of maize production is most likely associated with changes in production technology, the introduction of maize hybrids, and economic factors rather than as a result of climate change (Rosenberg, 1992). Soybean is highly sensitive to length of the crop photoperiod such that the geographic range of a particular variety is quite limited. The northern movement of soybean is partly or largely due to breeding new varieties adapted to longer summer days (Huffman and Evenson, 1993). In early years of the century the general expansion of agriculture westward into lands suitable for wheat in Oregon, Washington, and California contributed to the westward shift of mean production of that crop. Concentration of production of maize in the central U.S. partly at the expense of wheat grown there, thus increasing the production weight of western grown wheat, contributed to further shifts through the century.

Potential explanations for the change in variability are more complex but the fact that cropping was increasingly concentrated in areas better suited for production, the ability of farmers to adopt technologies to limit yield risk to climate factors such as irrigation, grain drying, and the effects of federal farm programs on production choices (Lewandrowski and Brazee, 1993) may be responsible for changes in variability to the extent they occurred. The more remarkable aspect of the data on long term variation in yields is that as a percent of yield it has remained nearly unchanged, as even the statistically significant trends are slight. A first reaction to this might be that it seems surprising that, with the tremendous technological developments over the past century, scientists and technologists have been unsuccessful in providing farmers with methods to reduce losses.

The case of technology development in maize production offers an example of the intertwined set of factors and reasons. Shorter-maturing varieties and widespread use of grain drying are 2 major developments in maize production. Both could have been employed to reduce the risk of loss due to early frost. The main effect, however, appears to have been to allow a northward expansion of production reflecting a willingness to accept risk of crop loss. At the same time, government policies to limit farmers financial losses may have increased their willingness to

accept yield losses (Lewandrowski and Brazee, 1993). With such strong social and technological forces operating, it is extremely difficult to sort out a pure climate effect from observed data.

One might evaluate individual sites but changing cultivars and practices mean that even such data would contain a mix of effects. It is unlikely that even experimental sites have grown the same varieties using unchanged practices for decades. Hence, even these very controlled situations will include technological and management signals that may overwhelm a climate signal. As briefly reviewed above, detailed investigations of individual cases can provide much insight into the proximate causes of some of these changes. At a broader level, however, underlying cause and effects are difficult to sort out as agricultural scientists and farmers are constantly searching for ways to limit weather and climate risks, and to increase production and expand areas suitable for production, whether climate is changing or not. Thus, sorting out either the direction of effect on yield of historic climate change or its magnitude requires a more detailed empirical evaluation than was possible here, and may be so intertwined that separating this effect from other factors is an artificial separation.

Whatever the effect of historical climate change, however, the evaluation we have conducted indicates that it is either small or overwhelmed by other forces, and so any long-term climate change signal in observed national yield and production trends is not readily observable. The evidence on the effect of variability is more easily observed in cross-section data (as farmers face the same technological opportunities at any given point in time) and we pursued that approach as discussed later.

### **3. Simulated Climate Change Impacts on U.S. Agriculture Production in 2030 and 2090**

We conducted an integrated assessment of climate impacts on U.S. agriculture. Five principal direct effects of climate change were considered. These involve the effects of climate change on

1. crop yields and irrigated crop water use,
2. irrigation water supply,
3. livestock performance and grazing/pasture supply,
4. pesticide use, and
5. international trade.

Figure 2 provides a diagram of the study elements, the models used, and how results were integrated to estimate the combined effect of these various changes on the agricultural economy, regional crop and livestock production, irrigation water use and irrigated area, and cropland and land use. This agricultural study was part of a broader U.S. National Assessment (National Assessment Synthesis



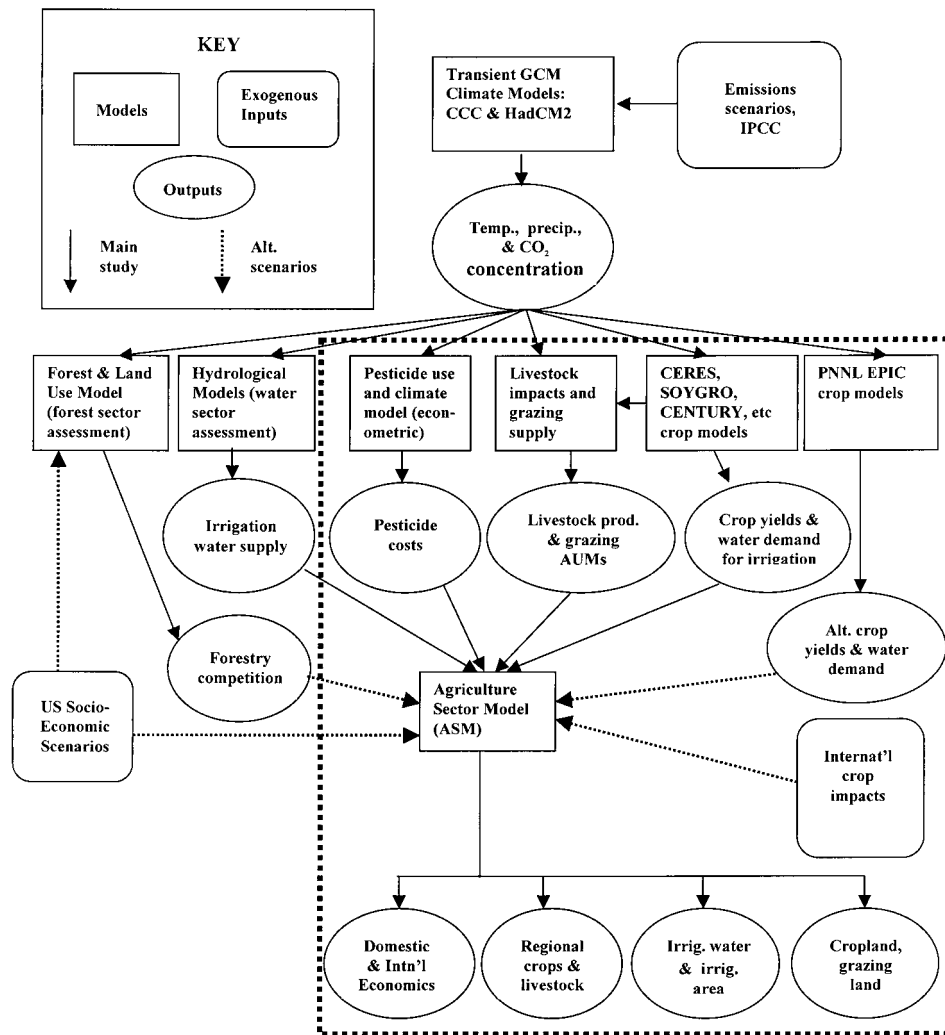


Figure 2. U.S. agricultural impacts modeling and analysis approach: Items inside heavy dashed line are elements of the agriculture sector assessment, those outside are results from other parts of the U.S. National Assessment.

Team, 2001) and benefited from the other components of the Assessment but was also limited by assumptions and limitations of those analyses. In particular and as illustrated in Figure 2, two different GCMs (the Hadley Centre HadCM2 and the Canadian Climate Center models) were used to create transient climate scenarios based on the IPCC's IS92A emissions scenario. The principal output from these scenarios used in our agricultural assessment was the mean monthly changes in precipitation and temperature and CO<sub>2</sub> concentrations. We thus investigated the combined effects of climate change and the direct effect of increasing ambient

CO<sub>2</sub> concentrations on crop yields. We used data for two future decades, the 2030s and the 2090s. The same climate scenarios were used to drive all components of the National Assessment.

One key input to our agricultural assessment was changes in irrigation water supply. The water sector component of the National Assessment provided data by river basin on changes in river flows based on hydrological modeling (Gleick et al., 2000). Reductions or increases were used to proportionally adjust the amount of water available for irrigation. The water sector did not consider how demand from other sectors might further impinge on supplies and hence we were not able to consider that affect. We also did not consider how changes in the timing of water flows (e.g., due to changing snowmelt) might compare with changes in the timing of irrigation water demand (e.g., as affected by changed planting and crop maturation), and what implications this would have for water storage and management. At least on the basis of snowmelt and crop planting and maturation, both supply and demand for water might be expected to shift ahead in the season but we were unable to explore this issue more rigorously.

Another issue of integration across sectors was the changing competition for land as it was affected by climate change from both forestry and agriculture. The forestry component of the U.S. National Assessment conducted a complete transient analysis whereas we conducted snapshot assessments for the decade of the 2030s and 2090s as it proved infeasible for us to run the crops models under a transient climate scenario. The forest sector assessment had overlapping team members with our effort and used a related economic model that included as a component the Agriculture Sector Model (ASM) used herein and in that study they used both agricultural and climate change sensitivity information to study land use competition (McCarl et al., 2000; Irland et al., 2001). We show a dashed arrow from this component as we focus here on the detailed results we generated from our snapshot assessment of the 2030s and 2090s decades but the results of the forest sector's transient analysis are comparable to those reported here.

The National Assessment also developed future socio-economic scenarios. These were used to inform our thinking about the future but the quantitative detail was insufficient to drive the economic model we used. We chose instead to impose the various climate driven changes to the agricultural economy as it existed in 2000. It would seem to make much more sense to use explicit assumptions about future conditions of the agricultural sector but in practice it turns out that when this has been done, the impacts often scale in proportion to reference growth in, for example, yields, the size of the agricultural economy, or production depending on what variable one is interested in (Reilly et al., 2002). As discussed in Reilly et al. (2002) this may reflect more the difficulty in thinking about key factors that affect the sensitivity to climate, a second order consideration, as attempts to project into the future tend to focus instead on first order factors that determine growth of production, yield, or the economy. But, these first order factors generally do not, in themselves, affect sensitivity to climate. While it is possible to develop a reference

scenario, independent of a climate change scenario that might include much greater sensitivities, there are problems of the time-consistency of such a reference scenario with the climate scenario. For example, a reference scenario where irrigation usage expands greatly throughout the southern U.S. would only be reasonable if water resources existed to supply such usage. If one imagined a reference where such an expansion was possible but then imposed a climate scenario where water resources gradually dwindled one would find much greater sensitivity to the climate scenario. However, in a realistic transient case farmers would stop expanding irrigation usage at some point if there were no water resources to supply it. As a result, looking at the sensitivity of the existing agricultural economy perhaps offers a sounder basis to think about directions that would make it less vulnerable to projected climate change, than to consider the sensitivity to a highly speculative future agricultural economy. In any case, the choice we made in this work was to impose the climate change on the current agricultural economy.

The components that were formally part of the agricultural assessment are shown within the heavy dashed box in Figure 2. The central integrating model was the Agricultural Sector Model (ASM). The ASM is based on the work of Baumes (Baumes, 1978), which was later modified and expanded (Burton and Martin, 1987; Adams et al., 1986; Chang et al., 1992; Lambert et al., 1995). Conceptually, ASM is a price endogenous, mathematical programming model of the type described in McCarl and Spreen (McCarl and Spreen, 1980). The U.S. is disaggregated into 63 geographical production subregions. Three land types (irrigated and dry crop land, pasture land, and land for grazing on an animal unit month basis) are specified for each region. Water for irrigation comes from surface and pumped ground water sources. The model distinguishes between primary and secondary commodities with primary commodities being those directly produced by the farms and secondary commodities being those involving processing. There are 33 primary crop and livestock commodities and 37 secondary commodities that are processed in the model. The demand sector of the model consists of the intermediate use of all the primary and secondary commodities, domestic consumption use and exports. The ASM includes explicit treatment of foreign regions, aggregated into 28 countries/regions. These features make the ASM model ideally suited to integrate the various direct impacts of climate change as estimated by the various models.

To consider the impacts of climate change on crop production we conducted crop modeling studies using the CERES and SOYGRO family of crop models at 45 sites in the U.S. for wheat, maize, soybean, potato, citrus, tomato, sorghum, rice, and the CENTURY model for hay and forage under dryland and irrigated conditions for two transient climate scenarios (Tubiello et al., 2000, 2002). We also were able to consider an alternative set of results for a limited number of crops and scenarios as estimated using the PNNL EPIC-based set of crop models (Izaurralde et al., 1999). The PNNL crop modeling system allowed us to consider how results depended on the crop model used. We also compared the crop models more directly for a limited set of simulations conducted at the same sites (Paustian

et al., 2000). Both these sets of models produced estimates of yield changes and changes in demand for irrigation water that, as shown in Figure 2, were the key inputs into the ASM from these crop modeling studies.

The 45 crop model sites used in the main study were chosen using USDA national and state-level statistics to cover major producing regions. Climate scenarios were developed from transient runs of 2 general circulation models (GCMs): the Canadian Center Climate Model (CC) and the Hadley Centre Model (HC) (National Assessment Synthesis Team, 2001). For the U.S. as a whole, the Canadian model predicts a 2.1 °C average temperature increase by 2030 and a 5.8 °C warming by 2095 with a 4% decline and 17% increase in precipitation, respectively. The Hadley Center scenario produces a 1.4 °C (2030) and 3.3 °C (2095) increase in temperature with precipitation increases of 6 and 23%.

Crop models were run for twenty-year average climates centered around 2030 and 2090. The deviations in temperature and precipitation from control runs of the GCMs were applied to actual 30-year weather records at each of the 45 sites. Yields were simulated for current varieties and planting schedules as well as for alternative varieties and planting schedules to consider the potential to adapt to the changed climatic conditions. The crop yield impacts used for the economic analysis were the difference between 30-year mean simulated yields under the historical weather and the historical weather adjusted by the GCM climate deviations. Atmospheric CO<sub>2</sub> concentrations used for the crop studies were 350 ppm for the baseline, 445 ppm for 2030, and 660 ppm for 2090 assuming that a proportion of the forcing used by the GCMs, consistent with the 1995 Intergovernmental Panel on Climate Change (IPPC) Business-as-Usual scenario, was from other greenhouse gases (IPCC, 1996).

The simulated yield changes were also used as proxies for changes in yields of related but unmodeled crops (barley, oats, sugar cane, and sugar beet) in order to estimate national crop production for all crops included in the economic model. Ideally we would have produced direct estimates with crop models for each crop but validated and tested models were unavailable for these crops. This has been an ongoing issue in agricultural impact assessment. Early assessments tended to focus on a very few grain crops, and use a proxy approach or highly simplified relations (growing degree days and general biomass production) for other crops. This has been seen as generally preferable to leaving productivity of other crops unchanged when introducing results into an economic model as the *relative* changes in productivity among crops is what is important in the economic model. (E.g., if yields of simulated crops decrease, that causes the economic model to switch toward production of crops whose productivity was left unchanged.) By including citrus, potatoes, and tomatoes as specifically modeled crops this study has included more crops than previous assessments. We also devoted effort to incorporating cotton, the most important crop in terms of value and a heat tolerant crop. While we had no cotton crop model available directly to the group and lacked expertise and time to test and evaluate a candidate model, we relied on cotton work arising in a project

led by an assessment team member that did not exactly match our assumptions (Mearns, 1999) as a basis for our estimates, with an evaluation of the different approaches we tried described in Reilly et al. (2002).

Changes in pesticide use were evaluated using an econometric model that was estimated using cross-section data to determine the dependency of these costs on climate (Chen and McCarl, 2001). The GCM forecast climate change was then used to estimate changes in pesticide expenditures based on the econometric model. Finally, estimates of the livestock performance sensitivity to temperature changes (generally a decline in weight gain or milk production with higher temperatures) arising in a previous study (Adams et al., 1999), were used to depict climate impacts on livestock productivity. A further component of the livestock effects model were estimates of changes in Animal Use Months (AUMs) and pasture requirements for grazing. These were based on estimates of changes in forage productivity as estimated by the crop models. The livestock model, shown as a separate box in Figure 2, is a submodel component of the ASM.

The outputs of the above models (water supply, crop yields, irrigation water demand, livestock performance, and grazing demands) were introduced into the ASM, described above, to find the integrated effect on the agriculture sector. Basically, the ASM models economic competitiveness among crops and growing regions. Thus, it models the relocation of the production of crops or livestock away from areas negatively affected toward areas positively affected. It also considers how demand for an agricultural product (used for livestock feed, in processed product production, or in final consumption) that has become relatively less scarce due to climate change might be used in place of others that have become relatively more scarce. Thus, the economic model might amplify regional and intercommodity yield effects by further shifting production (e.g., a region with severely negative yield effects would find an even greater reduction in production because in addition to less yield per acre the acreage devoted to the crop would be reduced as production shifted to other regions). Demand can have the opposite effect (e.g., if all yields decline, then prices would rise and more total acreage would be devoted to the crop so production would not fall as much as yield whereas if most yields increased prices would fall and less area would be devoted to production, and output would not increase as much as yield). What actually happens in a particular region is thus a complex result of the aggregate yield effect, demand, and relative changes among regions and crops.

A further consideration of the study was international trade effects. A variety of work has shown that the economic effects of climate change on a country's agricultural sector can depend on what happens to agriculture elsewhere in the world because of transmission of effects through international trade. It was not, however, possible to develop a new set of yield estimates for all regions of the world. Instead we developed a set of scenarios of yield effects for the 28 foreign regions in the ASM based on previous estimates of production shifts globally (Reilly et al., 1993; Darwin, 1999) and shown in Figure 2 as the dashed arrow into the ASM. Included

in these scenarios were cases where production generally increased elsewhere and cases where it generally decreased and thus the main results, where we assumed no climate driven change in other regions, was in between these various cases. The trade sensitivity results did not differ that much in terms of total economic effect from the main results presented below (Reilly et al., 2002).

Figure 3 provides the summary results of the changes in the regional production measured as a price-weighted index of crop and livestock production (and shown as percentage change from the reference), and changes in resource use (land, water, labor, and grazing land).

We also estimated the net effect in terms of economic welfare (the sum of changes in consumers' and producers' surplus) of the combined changes in crop yields including adaptation and CO<sub>2</sub> fertilization effects, water supply, irrigation demand, pesticide expenditures, and livestock effects was generally positive. The increase in economic welfare was \$0.8 billion and \$3.2 billion (\$U.S. 2000) for the 2030 and 2090, respectively, under the CC scenarios. The increase for the HC 2030 and 2090 scenarios was \$7.8 and \$12.2 billion, respectively. These gains were distributed unevenly among domestic consumers, foreign consumers and U.S. producers. U.S. producers generally suffered income losses due to lower commodity prices while consumers gained from these lower prices. Producers' incomes generally fell due to lower prices. Producer losses ranged from about \$0.1 up to \$5 billion. The largest losses were under the Canadian Center climate simulation in 2030. Under the Hadley center climate producers lost from lower prices but enjoyed considerable increase in exports such that the net effect was for only very small losses. Economic gains accrued to consumers through lower prices in all scenarios. Gains to consumers ranged from \$2.5 to \$13 billion, the largest gains with the Hadley Center simulated climate in 2090.

There were substantial regional differences with some regions suffering production declines under some conditions even though the overall production effect was positive. The CC scenario was much warmer and much drier, particularly in the 2030 period and thus the less positive effects on crop production overall and negative effects in the Southern and Plains areas of the U.S. The hot and dry conditions in this scenario had particularly negative effects on the major crops important in Southern (soybeans) and Plains (wheat) regions. At southern sites, dry land soybean yields declined as much as 70% due to the dry conditions. Rice and tomato yields also declined in the south, although citrus yields improved due to less chance of damage from cold weather. In the Plains sites, dry land winter and spring wheat yields declined by 10 to 50% in the CC scenario. With these types of yield declines (while yields of soybean and wheat improved elsewhere), these regions lost comparative advantage and production shifted elsewhere in the country for these crops. The HC scenario has more moderate warming and particularly large increases in precipitation and as a result we did not observe the severe yield declines observed under the CC scenario.

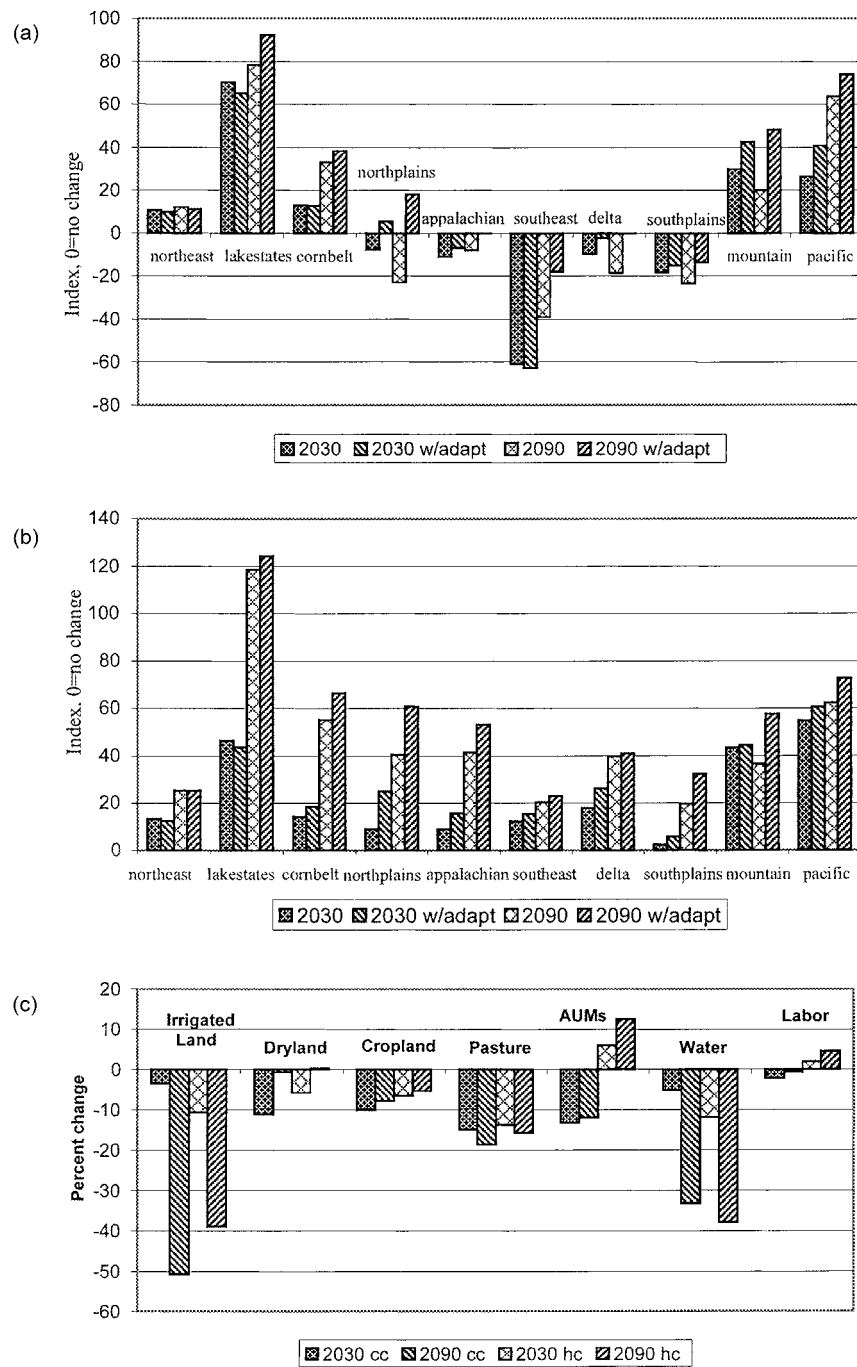


Figure 3. Simulated percentage changes in regional production and resource use under 2 climate scenarios. (a) Production changes under the Canadian Center Climate. (b) Production changes under the Hadley Center Climate simulation. (c) Land, water, labor, animal unit months (AUMs), and pasture use (cc: Canadian Climate model simulation; hc: Hadley Center model simulation).

The overall results showed a decline in the number of irrigated acres and in water demand for irrigation of between 5 and 35% (see Figure 3c for details), largely because of the differential effects of climate change on productivity of irrigated versus non-irrigated crops and declines in the use of most resources. Not surprisingly, use of nearly all of the resources shown in Figure 3 declined. This result largely reflects the fact that on net, climate change was productivity enhancing and the definition of an increase in productivity in economic terms is that the same amount of output can be produced with fewer total inputs. With price responsive demand, consumers will not increase consumption by as much as the productivity increase and therefore output will not rise enough to require as much inputs, in total, as were previously used. Climate change impacts did not affect all inputs equally and thus it need not be the case that every input decreased but, but in fact that was essentially the case. The productivity increase due to climate change was biased particularly to being water (and irrigated land)-saving. If the climate changes as represented in these scenarios, and these are only 2 climate scenarios and so one should not place excessive confidence in the results, there is potential that reductions in agricultural demand for resources could ease the growing competition for water from urban and environmental users and land for other uses such as preservation of natural systems.

Regional effects vary. There was considerable differences in how water supplies and demands changed regionally, driven by the regional patterns of climate change, cases in point being the regional studies we discuss later. With production shifting to Northern regions, cropland use expands there (though not nearly as much as output because yield per acre increases) while the contraction occurs particularly in the Southern and Plains states where, because of substantial yield losses in the CC scenario, agricultural production ceases to be viable on some land. With most irrigation water used in the West and Plains states, reductions in water use and irrigated land necessarily occur mainly in these regions.

In both scenarios there was a strong relative shift in advantage to dryland as opposed to irrigated cropping and this reflected significant differential effects on irrigated and dryland yields (or agronomic productivity to distinguish from economic productivity). Dryland cropping yields tended to benefit from higher precipitation, but that greater precipitation was of little value to the agronomic productivity of irrigated crops (they already are supplied with all the water they need). There is an economic productivity benefit of more rain for irrigated crops in that there is less need for purchased or pumped water. But, the agronomic productivity of irrigated crops actually fell at many sites and often substantially enough so that it offset any economic benefit of using less purchased or pumped water. The yield decline occurred because the higher temperatures speeded maturation and shortened the grain-filling period (the shorter growing period also meant less demand for water). While irrigated yields remained higher than dryland yields, irrigation is only economically viable if the yield difference is substantial. So, with the agronomic (and economic) productivity gap narrowing between irrigated and dryland crops,



irrigation became non-viable in many areas – hence the reduction in irrigated land – and, production shifted to dry land cropping, and more than likely to Northern regions of the country. Thus, several factors (climate, agronomic, and economic) contributed to the decline in water use.

The primary result of the trade sensitivity scenarios was to shift the estimated gains away from producers and toward consumers for cases where global production increased and toward producers and away from consumers for cases where global production decreased. This result appears due to the position of the U.S. in the world agricultural economy. As the U.S. is both a significant food consumer and exporter, increases in production outside the U.S. lead to consumer benefits from lower prices roughly balancing producer losses due to lower prices and fewer exports. The situation is reversed, but the changes roughly balanced, if global production changes cause world prices to rise. As a result, the net effect on the U.S. economy did not change much under different global impact assumptions.

Among the trade scenarios drawn were ones that showed both small increases and decreases in world prices (i.e., net reductions and net increases in global production). One caution in interpreting these results is that our study found generally larger increases in yields for the U.S. than had been observed for the U.S. in the studies from which these global impact results were drawn. If the more positive effects we observed for the U.S. held for other regions, then a global production increase (with most commodity prices declining) would be more likely than the opposite. Clearly, however, more international analysis is needed and a danger of conducting national assessments, such as this one, is that consistent global estimates for impacts of traded goods are unlikely to be generated if individual countries undertake uncoordinated assessments of climate impacts within their borders.

Adaptations not included in the economic model, such as shifting of varieties and planting dates were evaluated using the crop models. The effect of these adaptations were generally less in our study than in many previous studies, but this may reflect the fact that we may not have identified and evaluated the types of adaptations (e.g., double-cropping) that could have taken full advantage of the generally improving conditions. For the most part, yields for crops in many regions increased substantially even without adaptation measures. The exception was in the South and Southeast where yield reductions were particularly severe in the CC scenario. But here, adaptation measures were unable to erase the yield losses. Other economic adaptation such as changes in types of crops, irrigation, and input use are endogenously modeled within the economic model, and farmers are simulated to use more or less of these depending on their profitability in each region.

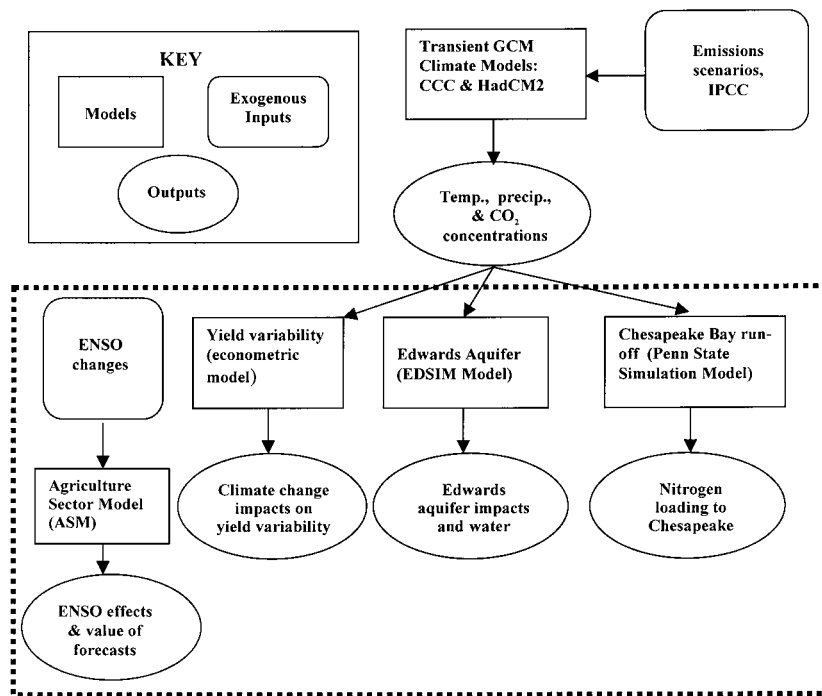


Figure 4. Case study models and methods. Agriculture sector assessment elements are inside heavy dashed box, other elements of the National Assessment are outside dashed box.

#### 4. Case Studies on Environmentally Vulnerable Areas and Variability

A third component of the study was a set of cases studies on environmentally vulnerable areas and variability. Figure 4 illustrates the cases, models and methods. These results were not integrated together with the simulations reported in the previous section or among these cases and so each of the modeling activities resulted in its own separate set of results as illustrated in the figure. Except for the ENSO study, each of the cases were driven by the same climate scenarios. ENSO (El Niño, Southern Oscillation) changes are generally not predicted in GCM studies and so to consider this potential change in variability we included results of recent work that suggested how ENSO event frequency might change. These scenarios involved only changes in ENSO frequency and intensity and no other general change in climate.

##### 4.1. AGRICULTURE-CLIMATE-ENVIRONMENT INTERACTIONS

Potentially important concerns of climate change are broader agriculture-climate-environment interactions. Beyond the aggregate water and land use results discussed above, we considered more detailed interactions. Our finding of increased expenditures on pesticides for major field crops was part of our aggregate results

discussed above. This change in pesticide expenditure (for most states and crops an increase of 10 to 20% on maize, 5 to 15% on potatoes, 2 to 5% on cotton and soybean, -15 to +15% on wheat) only reduced the benefits of climate change by about \$100 million because pesticide expenditures are only 3 to 5% of the total cost of production, although this varies by crop. We did not study the potential environmental implications of increased pesticide use but this is a concern that should be addressed in future studies.

We also examined the complex interactions of agriculture-climate-environment in the Edwards aquifer region around San Antonio Texas and nitrogen run-off into the Chesapeake Bay. In both of these regional studies, we found increasing threats to the environment under the climate scenarios. The Edwards aquifer region, contrary to most of the rest of country, becomes drier in these scenarios and this increases urban and agricultural demand for water. This case study utilized an existing model that integrated a hydrological model of the Edwards Aquifer and an economic-systems model – EDSIM (McCarl et al., 1998) – to examine the implications of climate-induced changes in recharge and water demand. The hydrological model included a model of surface springflows, recharge due to precipitation, and draw down from pumping. The economic model includes agriculture and urban demands for the water, and responsiveness of these demands to both climate and water prices. Water prices are calculated endogenously for different levels of constraints on pumping. It was found that resultant increased pumping of groundwater from the aquifer due to greater demand for water combined with reduced rainfall would threaten surface spring flows supported by the aquifer that are habitat for protected endangered species (Chen et al., 2001). Our estimates are that the regional welfare loss was estimated to be between \$2.2–6.8 million per year due to climate change. If springflows are to be maintained at the currently protected level, pumping must be reduced by 10 to 20% below current legislated levels at an additional cost of \$0.5 to \$2 million per year.

The study in the Chesapeake Bay region utilized a maize production model, a model of economic decision making, and a simplified version of a Generalized Watershed Loading Functions (GWLF) model and considered only the 2030 climate scenarios for HC and CC (Haith et al., 1992). The GWLF model was simplified through a reduced form fit of the model to data generated from a Monte Carlo analysis. Results of the simulations of this combined modeling system showed that climate change could increase nitrogen loadings to the Bay by 17 and 31%, the greater figure for the HC scenario (Abler et al., 2000). Taking advantage of enhanced productivity potential, maize production in particular expanded and total nitrogen use consequently increased. In the HC scenario substantial increases in rainfall led to greater erosion and run-off.

We evaluated alternative practices that, when implemented, reduced loadings on the order of 70% in all cases (i.e., from current loadings with current climate, and from the loadings under the alternative HC and CC climates without adoption of these practices). The nature of this modeling experiment was to evaluate whether

these practices effectively reduced loadings and whether their effectiveness depended on the particular climate. The similar percentage reductions can be seen as equivalent effectiveness in one sense but total remaining loadings are the more important criteria for water quality. Here there remained differences because of the fact that the altered climate scenarios had higher run-off in the first place. The environmentally friendly practices are not the current choice of farmers in the region and the presumption is that there would be additional costs or incentive payments required for farmers to adopt such practices but we did explicitly evaluate the extra cost. As water quality in the Chesapeake Bay is already a significant environmental problem, various changes in farmer practices may be mandated even without climate change or well before the 2030 period examined here.

Subsequent work using the models and approaches developed above has shown that corn prices as they are affected by climate change (and thus the area grown with maize), the degree of farmer response to climate change (do farmers expand production in response to improved productivity of maize) and whether a significant CO<sub>2</sub> fertilization effect is realized (with the additional growth, more of the nitrogen fertilizer is used by the plant and thus does not run-off) can also have large effects on nitrogen loadings (Abler et al., 2002). In a scenario when maize prices fell and there was a strong CO<sub>2</sub> fertilization effect loading decreased compared with current climate under both the HC (by 25%) and CC (by 33%). While in a case with higher prices and no CO<sub>2</sub> effect loadings were much larger (HC, +57% and CC, +37%) than our original estimate. Other cases gave intermediate results. These additional results show that climate is a strong factor in nitrogen loading but other changes that may accompany climate change may have equally strong effects on run-off. The CO<sub>2</sub> fertilization effect is likely to accompany climate change but not all of the forcing in a climate scenario is due to CO<sub>2</sub> and the strength of the fertilization effect is uncertain. And, if there is a strong fertilization effect that increases the likelihood that there will be increases in production in many parts of the country and world and increases the chance that maize prices will be lower. These feedbacks are uncertain, and in this work, are examined as alternative scenarios (e.g., the model focuses only on the Chesapeake Bay area, but maize prices are determined largely by supply and demand conditions in the broader national and global economy which are not represented explicitly).

## 5. Future Climate and Crop Variability

One of the more difficult areas of study is future change in variability. This is difficult because there are many dimensions of variability (daily, seasonal, interannual) and varied responses of crops to extreme conditions and extreme events. For example, whether a drought lasts 12 rather than 10 days and/or whether extreme temperatures occur during the very short period when crops are flowering can mean the difference between crop failure and minimal impact (Mearns et al., 1984,

1996). The climate scenarios produced by general circulation models provide some information on changes in climate variability. Most climatologists however, doubt the reliability of these projections because of the coarse resolution of the models and because the forces that create climate variability result from processes that operate below the grid scale resolution of the GCMs. All of these issues mean that there are many research questions that could be asked and many ways to approach such studies, but leaving considerable uncertainty in any results.

We asked 2 questions: (1) Is there evidence that changes in the mean climate conditions as predicted by the 2 climate scenarios we investigated could change the variability of yields; i.e., simply increasing the mean climate conditions can mean a substantial increase in extreme events and this might consequently increase the variability of yield. (2) What would be the economic impact on the US if El Niño-Southern Oscillation (ENSO) intensity and frequency increased as projected by one recent study (Timmermann, 1999).

Our analysis of changes in the variability of yield due to changes in mean climate conditions was based on a cross-sectional econometric analysis (Chen et al., 2001). The econometric model explains variability in yield as a function of mean temperature and precipitation and relies on the ability to separate changes in yield variability from changes in mean yields; i.e., changes in temperature or precipitation may affect mean yields and it may affect variability of yield but those effects can be estimated as separate econometric models. The results are given in Table II and show fairly uniform decreases in maize and cotton yield variability for climate change under the two climate scenarios with mixed results for other crops. Wheat yield variability tends to decrease under the HC climate and increase under the CC. Soybean yield variability shows a uniform increase with the HC. The principal reason for decreases in variability of yield was that the statistical results showed increases in precipitation to be variability-reducing and there were substantial increases in precipitation in these climate scenarios for most regions. The exception was for wheat growing regions, several of which had decreased precipitation, particularly in the CC scenario.

The El Niño-Southern Oscillation phenomenon (commonly referred to as ENSO) has observable effects on the weather in many parts of the world. Southern oscillation refers to a seesaw shift in surface air pressure at Darwin, Australia and the South Pacific Island of Tahiti. When the pressure is high at Darwin it is low at Tahiti and vice versa. El Niño and La Niña are the extreme phases of the southern oscillation, with El Niño referring to a warming of the eastern tropical Pacific, and La Niña a cooling. ENSO has very strong effects on Australian and South American climate but has weaker and mixed effects on the U.S. climate with some areas wetter and some dryer with each phase. ENSO events have been documented for hundreds of years, occurring with varying frequency and intensity.

Our evaluation of ENSO made use of the ASM model and techniques previously developed to evaluate the present day impacts of ENSO (Adams et al., 1995, 1999). The basic methodology was to estimate a baseline scenario where farmers

Table II  
Simulated percentage changes in yield variability due to changes in mean climate for simulated 2090 conditions for 2 climate scenarios

	Canadian Center Climate Change Scenario					Hadley Center Climate Change Scenario				
	Maize	Soybeans	Cotton	Wheat	Sorghum	Maize	Soybeans	Cotton	Wheat	Sorghum
CA			-12.84					-11.81		
CO				34.43					-10.60	
GA			-10.35					-6.92		
IL	-25.71	21.28				-24.73	18.90			
IN	-8.73	8.06				-26.31	20.30			
IA	-36.89	33.14				-26.83	20.90			
KS				-14.39	-0.75			-7.97	-18.16	3.38
LA			-13.03							
MN		4.01					10.60			
MT				32.86					-6.36	
MS			-13.92					-7.73		
NE	15.30	-4.74		48.22	-16.15	-15.05	11.65		-5.57	-1.72
OK				16.34	-9.27				-17.07	2.83
SD	-21.75			-6.94			-24.37			-19.10
TX			-13.21	27.86	-10.83			-8.05	2.26	-3.10

plant crops and undertake farming practices based on long run average weather conditions and observe the simulated economic effects under neutral, La Niña and El Niño phases of ENSO. The differences that result in the La Niña and El Niño phases from neutral climate conditions are thus the impact of ENSO events.

A further aspect of this analysis is an estimate of the value of knowing ahead of time the actual ENSO phase that will occur. Here, additional simulations are made where farmers optimize their planting and production practices for each ENSO phase, on the assumption that it can be predicted before they must commit to their planting and practice choices. We then compare the economic losses due to ENSO when farmers know ahead of time the ENSO phase with those cases where they do not know the phase. The reduction in losses is then interpreted as the value of having an accurate forecast.

Previous work examined the value of forecasting ENSO events based on their current average frequency and intensity. In this work, we extended that analysis to consider the agricultural impacts if the average frequency of ENSO increased and if the average intensity of ENSO increased. We found that, where farmers operate without information on ENSO, an increased frequency of ENSO caused an average annual loss of \$323 million (Chen et al., 2001). When both frequency and strength shifts were considered the loss increased to a \$1,008 million annual average, about 5% of typical U.S. agricultural producer net income. With forecasts of the ENSO events, farmers could avoid some of these losses through changes in practices. Under current ENSO conditions the value of improved forecasts was estimated at \$453 million on average annually. This rose to \$544 million under changed frequency of ENSO and to \$556 million with changed frequency and intensity. The value of improved forecasts did not increase as much as did the losses, indicating that much of the increased loss could not be avoided through better forecasts of ENSO frequency and intensity.

A necessary caution here is that the projections of the relationship between GHG-induced warming and ENSO are even more uncertain than other aspects of climate change, with differing results as to whether intensity and frequency would increase or decrease. The study we used as the basis for producing scenarios of changes in ENSO strength and intensity with climate change (Timmermann, 1999) is just one study and whether such increases would actually be observed with climate change remains subject of scientific debate.

## 6. Conclusions

We investigated the impacts of climate change and the direct yield-enhancing effects of rising concentrations of atmospheric CO<sub>2</sub> on U.S. agriculture using two recent GCM-derived scenarios. We found that overall climate change would be beneficial to crop productivity, although there are strong regional differences with possible declines in production in the Southern U.S. The benefits increased in 2090

compared with 2030 for both climate scenarios even though temperature increases were quite high by 2090 in the CC case. These results show the danger of attempting to summarize the impacts of climate change as a simple function of global mean temperature or to characterize losses from climate change as increasing over time, as much of the current literature has done. The fact that climate change was positive for the U.S. agricultural production, particularly under the fairly extreme high temperature scenario in the CC case for 2100 was surprising. Previous work using similar crop modeling methods has tended to find negative overall effects at these higher temperatures. The fact that these were transient climate scenarios and that precipitation increased substantially may explain this difference.

There remain many caveats to a study such as this. One of the largest uncertainties is that the climate projections remain highly uncertain and, on that basis alone, the results we present should be considered a study of the sensitivity of agriculture to these particular scenarios and not bounding cases of the possible effects, or necessarily central estimates of the effects. The Canadian Climate Center model produces relatively extreme high temperatures compared with other climate models whereas the Hadley Center model produces temperature increases closer to the middle of existing climate models, but it produces particularly high levels of precipitation increases for the U.S. There are also uncertainties in the methods and models we used to estimate impacts. Our approach for evaluating the impacts of pests was indirect, examining the impacts of weather on pesticide expenditures rather than modeling or evaluating specifically how pest populations might change, and this leaves open the possibility that some pest losses might be uncontrollable so that pesticide expenditures may only partially account for pest losses. The impacts of variability remain incompletely described and integrated into such assessments. We made much progress but much remains to be done, and in large part this depends on more accurate forecasts from climate models of how the details of weather might change with climate change. Our results were imposed on the agricultural economy as it existed now (year 2000) and this has some limitations as the agricultural economy is likely to change in many ways over the century, and this aspect of our methodology needs to be remembered in thinking about the results.

Our comparison of different crop models showed there to be some significant differences, particularly for irrigated crops. A more complete intermodel comparison among crop models would reveal the extent of these differences so that they could be resolved or recognized more fully as a factor contributing to uncertainty in projections of the type we undertook. There remain issues of how well crop models predict under extreme events. The climate scenarios we evaluated were surprisingly 'wet' and crop models may be particularly limited in their ability to estimate the damaging effects of excess moisture. Also, further inclusion of models of additional specific crops would be useful. Future research might investigate these basic research questions, and where we have tried for the first time to estimate an impact, such as on pesticide costs, more work using different methods to confirm these results would be useful. Finally, the development of a more integrated modeling



approach would make it possible to more readily analyze a wider variety of climate scenarios to more fully understand uncertainty in forecasts. The approach we pursued, which has become a standard approach for agriculture impact assessment, requires considerable researcher time to set up and run crop models for different scenarios and different sites. This provides a practical limit on the number of sites and scenarios that can be investigated.

The risks from climate change to agriculture will more likely occur at regional levels, depend on changes in precipitation or changes in variability of climate, or stem from more complex climate-agriculture-environment interactions, and this study was among the first to seriously explore these effects. In particular we found increased risks due to ENSO, to nitrogen loadings in the Chesapeake Bay, and to ecosystems dependent on the Edward's aquifer in Texas. The need to protect such environmental assets would require changes in agricultural practices that would, in turn, increase production costs. Much more study is needed here with a more complete assessment of environmental effects of climate change. On the positive side we found that for the U.S. as whole, water demand from agriculture would decrease under these scenarios, lessening competition with growing urban demand.

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(Received 15 October 2001; in revised form 22 July 2002)